8-1981

An Analysis of the Behavior of Steel Liner Anchorages

Daryl R. Armentrout
University of Tennessee - Knoxville

To the Graduate Council:

I am submitting herewith a dissertation written by Daryl R. Armentrout entitled "An Analysis of the Behavior of Steel Liner Anchorages." I have examined the final electronic copy of this dissertation for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Doctor of Philosophy, with a major in Civil Engineering.

Edwin G. Burdette, Major Professor

We have read this dissertation and recommend its acceptance:

J. E. Aiken, G. W. Goodpasture, C. W. Lee

Accepted for the Council:

Carolyn R. Hodges

Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)

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Accepted for the Council:

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Vice Chancellor
Graduate Studies and Research

AN ANALYSIS OF THE BEHAVIOR
OF STEEL LINER ANCHORAGES

A Dissertation

Presented for the

Doctor of Philosophy

Degree

The University of Tennessee, Knoxville

Daryl R. Armentrout

August 1981

ACKNOWLEDGMENTS

The author wishes to thank his major professor and advisor, Dr. E. G. Burdette, for his encouraging remarks and friendly criticism and for his direction and guidance throughout this study. Acknowledgment is also extended to the author's committee, including Drs. D. W. Goodpasture, C. W. Lee, and J. E. Akin. A special thanks to Dr. J. E. Akin for his technical assistance in the application of the PAFEC 75 computer program; without it, the results of this work would not have been possible.

ABSTRACT

The purpose of this study was to analyze the load-deflection behavior of liner anchorage systems used in the design and construction of steel-lined concrete containment structures in nuclear power plants. Both an angle, 3 × 3 × 1/4 inch, and a structural tee, WT 4X7.5, embedded in concrete were analyzed using two dimensional plane stress finite element models. Specifically the PAFEC 75 computer program with its bilinear stress-strain capability was used. The intent of this investigation was to produce analytically similar results to those measured in anchorage tests conducted by The University of Tennessee, Knoxville.

These tests produced curves of the load-deflection behavior that increased nonlinearly in deflection under increasing load to a maximum and then fell off with increasing deflection as the load decreased. The primary focus of this investigation was to demonstrate that analytically one can generate accurate load-deflection curves up to the maximum or "peak."

Five different analyses were made. Four of these were variations in the angle anchorage system and the fifth was an analysis of a structural tee. The comparison between the analytical and test results showed very close agreement in the ascending region of the load-deflection curve. As the analysis approached the "peak," it was not possible to analytically describe the crown of the curve simply with the bilinear capabilities of the finite element program.

In large measure, crushing of the concrete occurs as the load approaches the maximum "peak." In order to make rough approximations of this behavior, this investigator used a series of successive analyses where selected elements of the concrete mesh were eliminated. The elements that were eliminated for successive analyses were the first ones to reach strains where crushing of the concrete could occur. This approach appeared to give very conservative results compared to the test data. But, these analyses would be expected to give larger deflections than if the material could be modeled with changing properties of concrete crushing.

It is recommended that additional research be done to analytically predict the crushing behavior of concrete, particularly in the declining portion of the load-deflection curve. Also, the techniques used in describing the finite element mesh have practical application for use by investigators who wish to study other anchorage types and sizes. The ease in data preparation of the PAFEC 75 finite element program and the specific boundary conditions described between the anchor and concrete has practical application for future investigations. Specifically, this means that the interfaces between the anchor and concrete and the liner plate and concrete were described by the finite element mesh so that tensile and shear forces would not develop, which cannot happen in the test case.

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CHAPTER I

INTRODUCTION

Concrete containment vessels lined with a leak-tight steel membrane are used in about 48 percent of the containment structures of operating nuclear power plants and nuclear plants under construction in the United States (9). Concrete vessels provide the necessary radiation shielding of the contained fission products following a reactor accident; however, due to the porous nature of concrete and the possible presence of micro-cracks, the concrete vessels are likely to leak if the vessel is not lined with a leak-tight membrane.

In the United States the steel plate thickness varies from 3/16 inch to 1/2 inch. In Europe and Canada the inside face of some of the concrete vessels is painted with an epoxy to provide a leak-tight membrane (6, 15). To date, this practice has not been accepted in the United States.

Steel plate has been used both for reactor vessels and free standing containment vessels. Unlike the free standing steel vessels, the steel liner in combination with the concrete vessel makes little contribution to the overall structural strength. The concrete vessel is solely evaluated on its posttensioning and/or reinforcing steel characteristics so that the steel liner can be as thin as practicable. The liner must be strong enough to withstand the induced stresses and strains without rupture.

Functionally, there is no difference between the steel liners in a reactor vessel and a containment vessel (19). The liner in the reactor vessel is more exposed to irradiation, and insulation is attached to the front of the liner. Cooling pipes are attached to the back to control the thermal stresses. The liner in the containment structure is attached to the inside of the concrete vessel by either Nelson studs or continuous angles or tees. A key difference between the design criteria for reactor vessel liners and containment liners is the fact that in containment liners the liner cannot be "used as a strength element." However, "interaction of the liner with the containment shall be considered in determining liner behavior" (8). The primary function for both the reactor vessel liner and the containment vessel liner is to provide a leak-tight barrier. Since the containment vessel is subjected to significantly lower temperatures, a less complex liner system is required.

The main focus of this research will be directed toward the behavior of liner anchorage systems in containment vessels.

CHAPTER II

REVIEW OF PRESENT KNOWLEDGE

The design of steel liners for concrete containment structures historically has been based on steel pressure vessel practices. The fabrication methods, inspection practices, and material requirements have generally followed the provisions of Section III, Nuclear Vessels, of the ASME Boiler and Pressure Vessel Code. However, since about 1975, these requirements have been covered by the joint ACI and ASME "Code for Concrete Reactor Vessels and Containments" (8).

The liner is not a free-standing structure capable of resisting the internal pressure, but it acts compositely with the concrete vessel. However, it is considered to be stressed biaxially as a series of plates restrained by their attachments to the concrete (19). One plate is assumed to be buckled so that the stresses are released in the series of plates in accordance with the flexibility of the attachments to the concrete.

The principal criterion in the design of the steel liner considers various loads caused by pressure, concrete inelastic action, thermal expansion, seismic motion, concrete posttension, and other mechanical loads of attached structures and assures that these loads and combination of loads do not cause leakage through failure of the liner (1, 10). In order to assure reliability against leakage, the design requires that for posttensioned vessels the liner always remain in compression. However, for a conventionally reinforced concrete vessel, the liner would also be always in compression under a thermal increase inside containment. The formation of a crack that could allow leakage is remote unless tensile stresses develop in the liner. The only strength requirement for the liner as a self-supporting structure stems from stability considerations during the erection before and during the pouring of concrete. The liner serves as an inside form for the concrete containment structure.

The following loads are taken into account in the design of liners for containment vessels. The liner plate is designed so that it will remain leak tight while being subjected to the following loads; however, the liner plate is assumed not to furnish strength to the containment structure for any of these loads or loading combinations (8, 10). The overall concrete containment structure is analyzed for these loads and loading combinations, and the resulting strains at the interior surface of the concrete vessel are induced in the liner.

1. Loads are induced in the liner when the concrete vessel is posttensioned. The liner is considered to take the same strain associated with the concrete structure, but it has no strength contribution.
2. Internal pressure and thermal loads are included in the concrete vessel analysis. Normal operating temperature gradients are considered, but the most severe condition occurs from transient temperatures and pressures resulting from a loss-of-coolant accident.
3. The steel liner is not designed to resist earthquake loading. The integrity of the steel liner during a seismic event

depends upon the ability of the concrete structure to avoid large deformations. Also, the relatively narrow spacing of the anchors preclude large amplitudal buckling.

4. Live loads, such as weights of moveable equipment plus their associated impact loads, are applied to the liner as required. Particular attention is given to construction live loads such as the hydrostatic pressure of the wet concrete and wind loads on the liner plate during erection.

5. Shrinkage and creep of concrete are factors recognized to contribute somewhat to the loading conditions of the liner; however, the overall effort is believed to be small and therefore is not included in a numerical analysis.

The majority of these loads cause compressive stresses on the liner. The one exception is internal pressure which causes hoop and axial tensile stresses.

Various failure modes are considered in the analysis of steel liners for concrete containment structures (13, 20). The following conditions are summarized as follows:

1. Small amounts of elastic and inelastic buckling probably are not detrimental to the structure unless buckling causes other types of failure such as rupture of the liner plate.

2. Rupture of an anchor will in effect increase the spacing between the adjoining anchors. This will in turn reduce the load carrying capacity of the liner segment, thus increasing the shear load on the next anchor. A chain reaction may then follow, rendering the structure functionally inadequate.

3. If a sufficiently high tensile stress is developed in concrete in the shear anchor zone, ensuing cracking may cause concrete failure. To prevent this mode of failure, tensile stresses near the inside face of the concrete wall should be limited under all loading conditions. Concrete may also fail in compression and shear. Nonuniform straining of the vessel liner will induce relative displacement of liner and concrete. This relative movement causes bearing stresses at the interface between anchors and concrete, ultimately with crushing of the concrete occurring. All tensile stresses at the interface between the anchor and concrete are considered to be zero with the resulting cracking occurring.
4. Other modes of failure such as rupture of liner, low cycle fatigue, and brittle failure as a result of radiation fatigue are less likely to occur but are simply mentioned in the literature.

Three works by Tan (20), Lee and Gurbuz (16), and Chapman (7) are particularly valuable to the subject of liners and liner anchorage systems and promote an extensive bibliography of references. The first two are directly concerned with the subject of reactor vessel liners, much of which is also applicable to containment liners. The work by Chapman deals with equipment liners for fast breeder reactors and is referred to primarily because of its extensive bibliography. Other works of particular interest and value are those by Chan and McMinn (5) and Kicher (14) on the subject of liner buckling. Also of special interest on the subject of liner analysis are the works by Parker (18), Doyle and Chu (11), and Young and Tate (22). A later work by Winstead, Burdette, and Armentrout (21) presents a method of analysis based on the earlier work of Parker and is also consistent with the method presented by Doyle and Chu and the stress fall-off concepts described by Young and Tate. The work of this paper will not address the analytical aspects of a liner anchorage system. It will, however, focus on the load-deflection behavior of typical anchorage systems used currently in containment structure design. Reference 10 presents the analytical method used in evaluating the adequacy of the liner anchorage system for the Tennessee Valley Authority's Bellefonte Nuclear Plant. While the analysis method is accurate within the limits of the assumptions on which it is based, the factor that determines the final accuracy and usefulness of the analysis method is the availability of representative data on load-deflection behavior of anchors.

This method was the principal focus of the work by Burdette (3) and Burdette and Rogers (4).

CHAPTER III

REVIEW OF FULL-SCALE TESTING PROGRAM OF LINER ANCHORAGES CONDUCTED AT THE UNIVERSITY OF TENNESSEE, KNOXVILLE

Tests conducted in 1969 by the Bechtel Corporation on the load-deflection behavior of a liner anchorage system were somewhat inconclusive due primarily to the instability of the test specimen (17). Since other known test data were not available in early 1973, the Tennessee Valley Authority contracted with The University of Tennessee, Knoxville, Civil Engineering Department, for the testing of liner anchorages similar to those used in the design of the primary containment for the Bellefonte Nuclear Plant. The primary purpose of the testing program was to establish a load-deflection relationship for the anchorage to be used in the Bellefonte containment and thus to verify the adequacy of the design of the liner anchorage system. The load-deflection relationships used in the original investigation of this liner anchorage system were based on inadequate data as reported in Tan (19), the Bechtel tests (17), and assumptions made by TVA (10). The purpose of this discussion will be to comment specifically on the adequacy of the types of anchorages tested, pointing out the parameters that affect the results.

Basically two types of anchorages were tested in 1974 (3, 4). A 1/4-inch steel plate was anchored to a concrete block by a steel 3 × 3 × 1/4-inch angle. The angle length was 12 inches. The second type of anchorage was a structural tee. Both 4- and 6-inch tees, 12 inches long, vertically welded to the liner were tested. In 1980 additional tests were made at The University of Tennessee (2). These tests included structural tees and studs. Unlike the liner plate anchorage tests performed by the Bechtel Corporation, these tests were "pull-out" tests rather than "push-out" tests. The liner plate in the Bechtel tests was loaded in compression because the liner in the prototype acts in compression; however, the liner plate loaded in compression in the Bechtel tests had stiffeners to prevent buckling of the plate. The pull-out loads where the liner plate was loaded in tension did not require stiffeners. These stiffeners are not part of the anchorage system in the prototype structure. Based on the limited results of the Bechtel tests compared to the results of The University of Tennessee tests, it appeared that the method of loading, whether by tension or compression, had minimal effect on the test results. The main problem with the Bechtel tests involved instability of the specimen during testing, thus rendering incomplete data.

Five parameters have a major influence on the load deflection behavior of the anchorage systems. These parameters are weld length, orientation of angles, void length, concrete strength, and anchor type. In The University of Tennessee tests, voids were cast in the concrete at the junction of anchor and plate in selected specimens to simulate honeycombing of the concrete. Various void lengths ranging from 3 to 6 inches to the full length of the anchor were tested. Results of the tests are presented later herein as a basis of comparison for the analytical results discussed in Chapter IV.

CHAPTER IV

FINITE ELEMENT MODEL ANALYSIS OF LINER ANCHORAGES

A two-dimensional plane stress finite element model was used to analyze the resulting deflection of the liner anchorage under various loads in the liner plate. This analytical work was done to compare and verify the experimental work done at The University of Tennessee, Knoxville, in testing angles and structural tees embedded in concrete and welded along one edge to a steel liner plate. The angle size was $3 \times 3 \times 1/4$-inch and the tee size was WT4 × 7.5. The concrete blocks were 30 inches long in the direction of loading, 36 inches wide, and 27 inches high as shown in Figure 1. The finite element analysis represents a slice through the center of the test model. The PAFEC 75 computer program was used in the analysis. The primary feature of the PAFEC 75 program that contributed to this work was its ability to analyze a material with a bilinear stress-strain relationship. This feature was essential in evaluating the behavior of the concrete in the region of the embedded anchor.

A plot of the finite element mesh is shown in Figure 2. This mesh contains 194 elements and 670 nodes. Variations of this mesh are shown in partial views in Figures 3 through 7 representing the different conditions analyzed. Particular attention was given to the boundary conditions in order to represent the test specimen as closely as possible. External restraints are shown in Figure 8. In this figure the model is free to slide along the surface A-B which represents the actual test

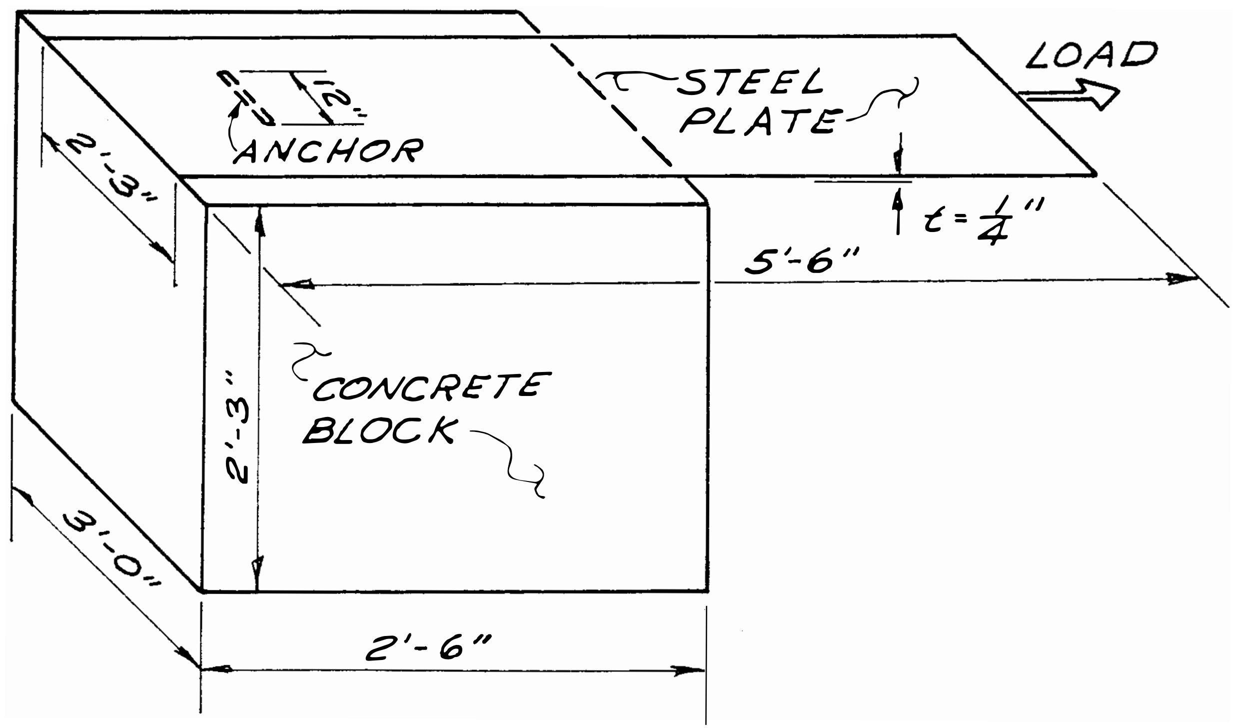

Figure 1. Sketch Showing Dimensions of Specimen

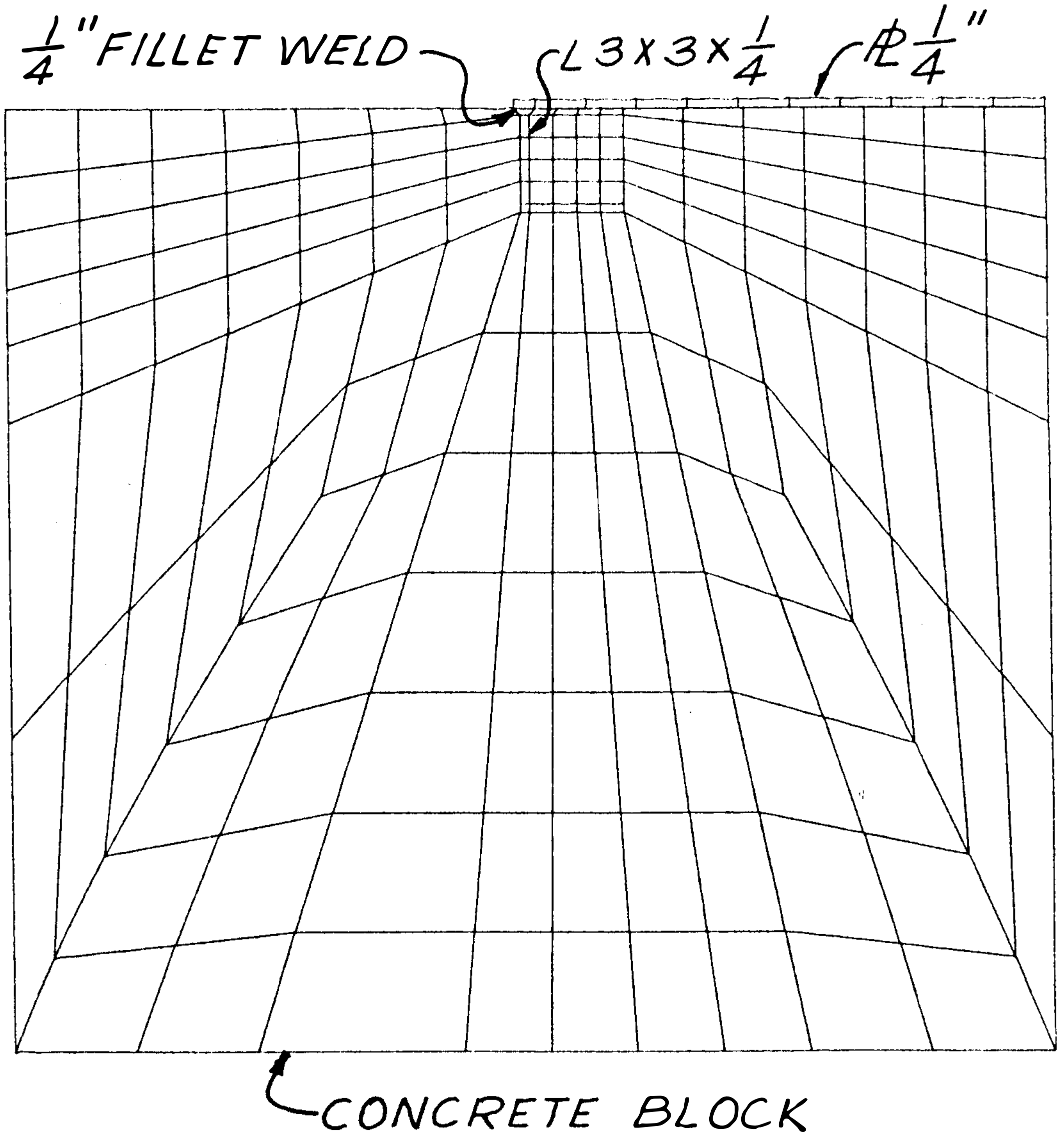

Figure 2. Finite Element Mesh of the Model of a Steel Liner Anchor Embedded in Concrete

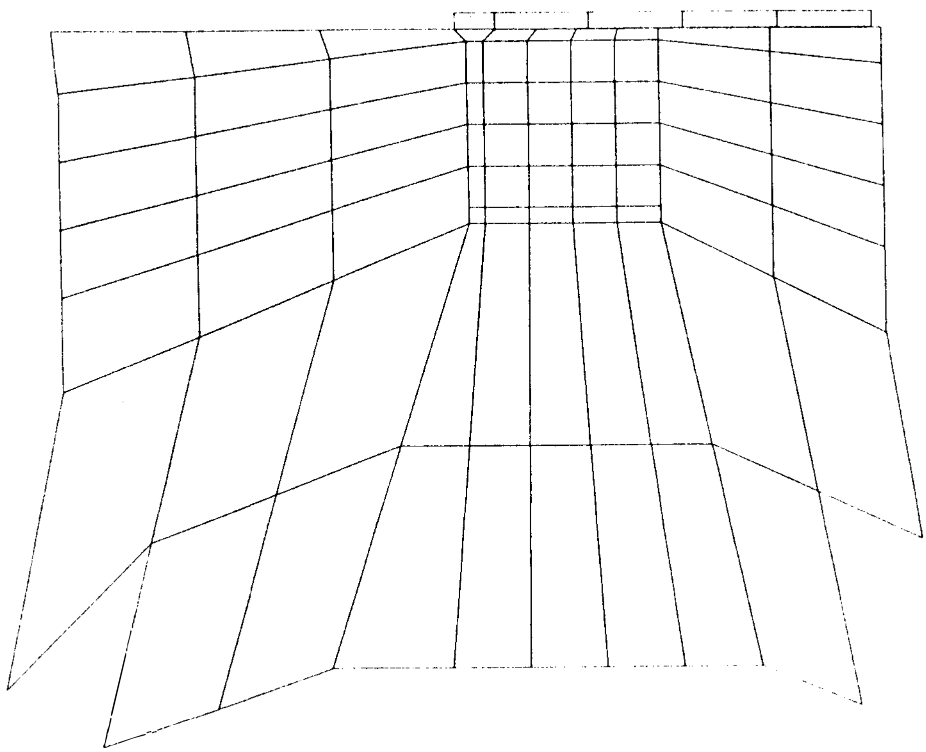

Figure 3. Partial Finite Element Mesh for Analytical Model DAR9

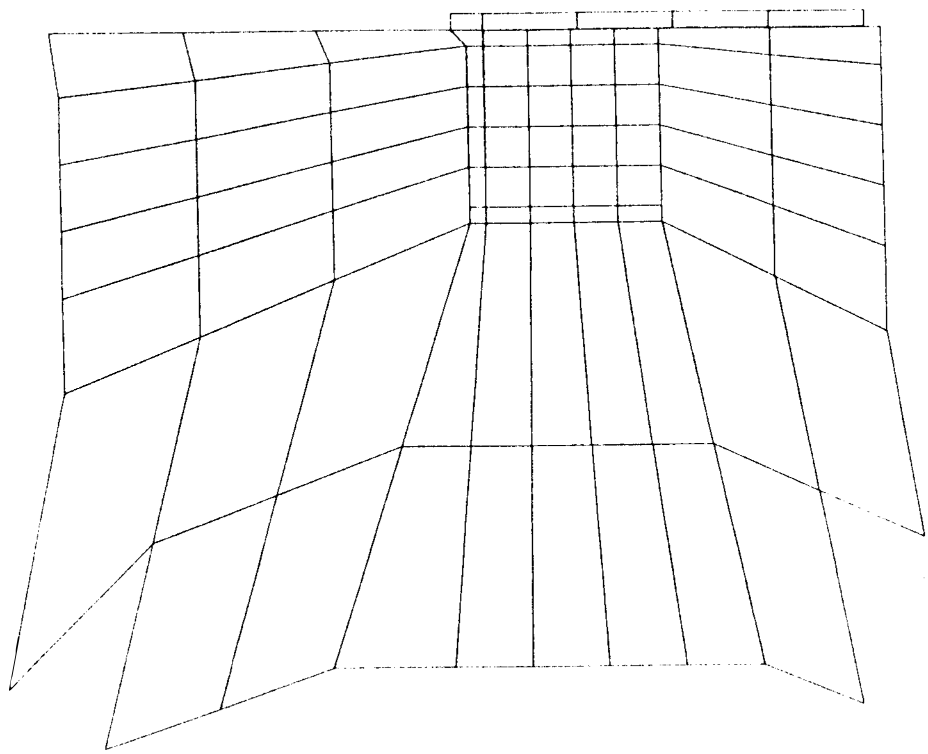

Figure 4. Partial Finite Element Mesh for Analytical Model RAD9

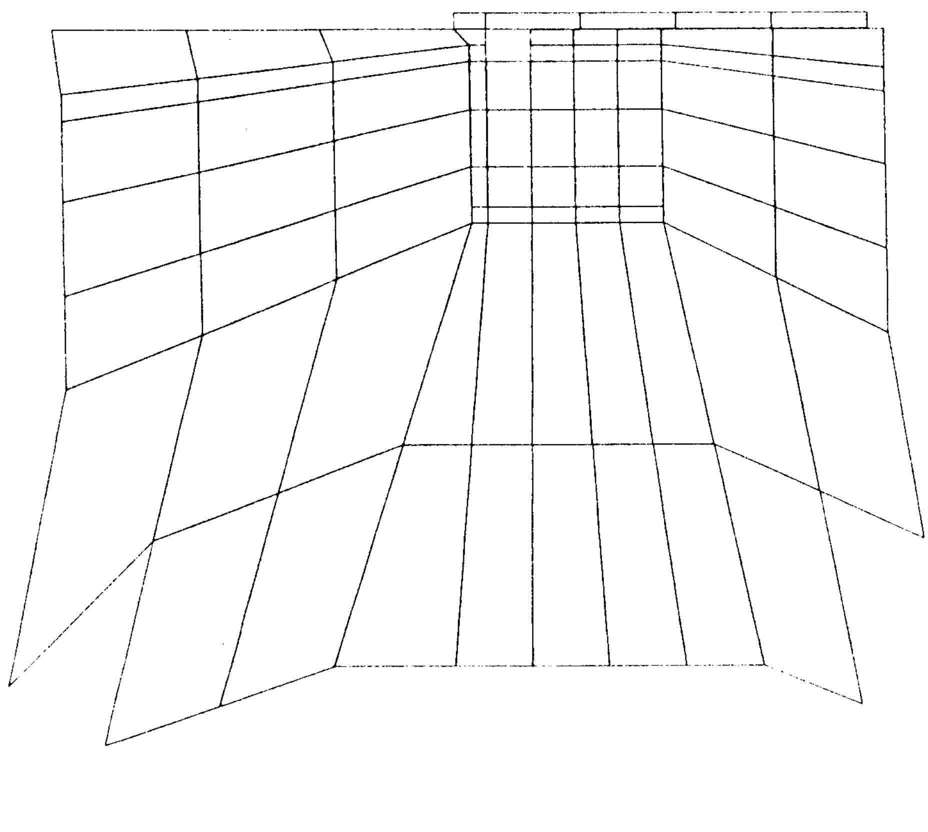

Figure 5. Partial Finite Element Mesh for Analytical Model ARD7

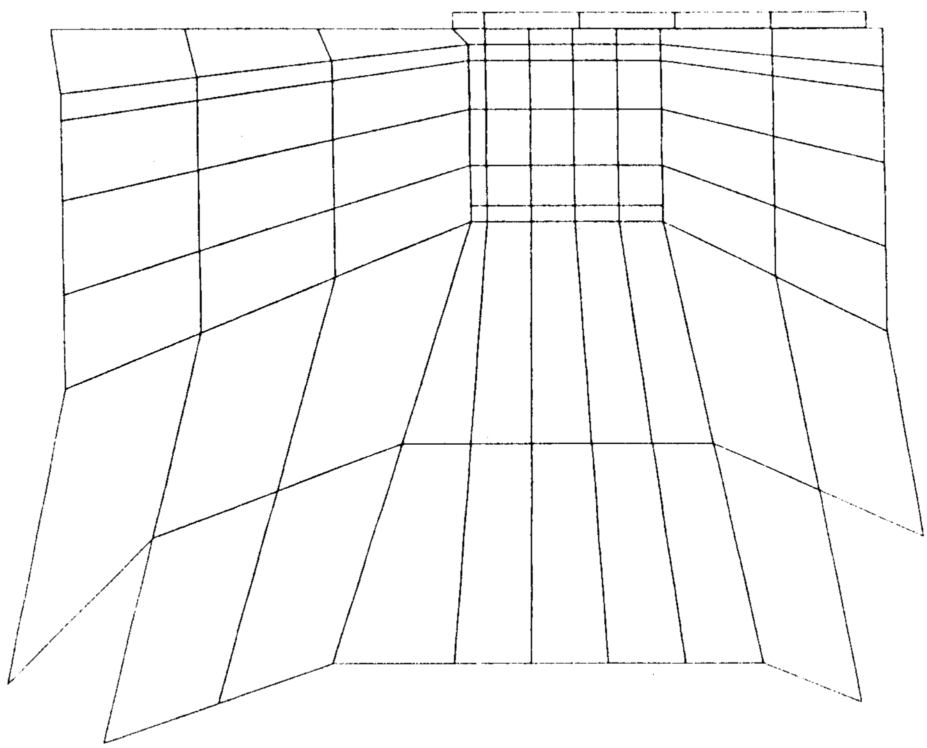

Figure 6. Partial Finite Element Mesh for Analytical Model ARD9

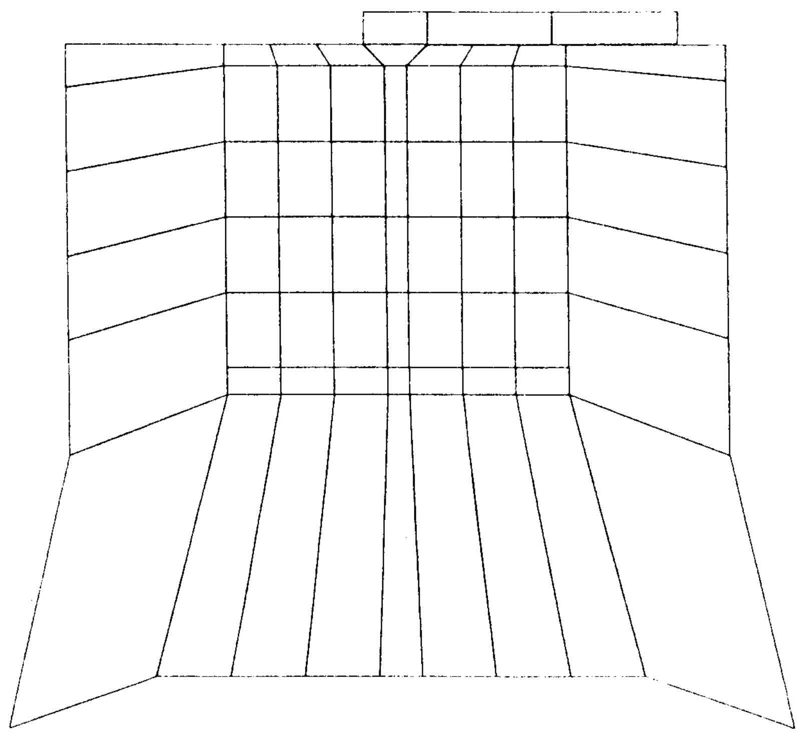

Figure 7. Partial Finite Element Mesh for Analytical Model ARD8

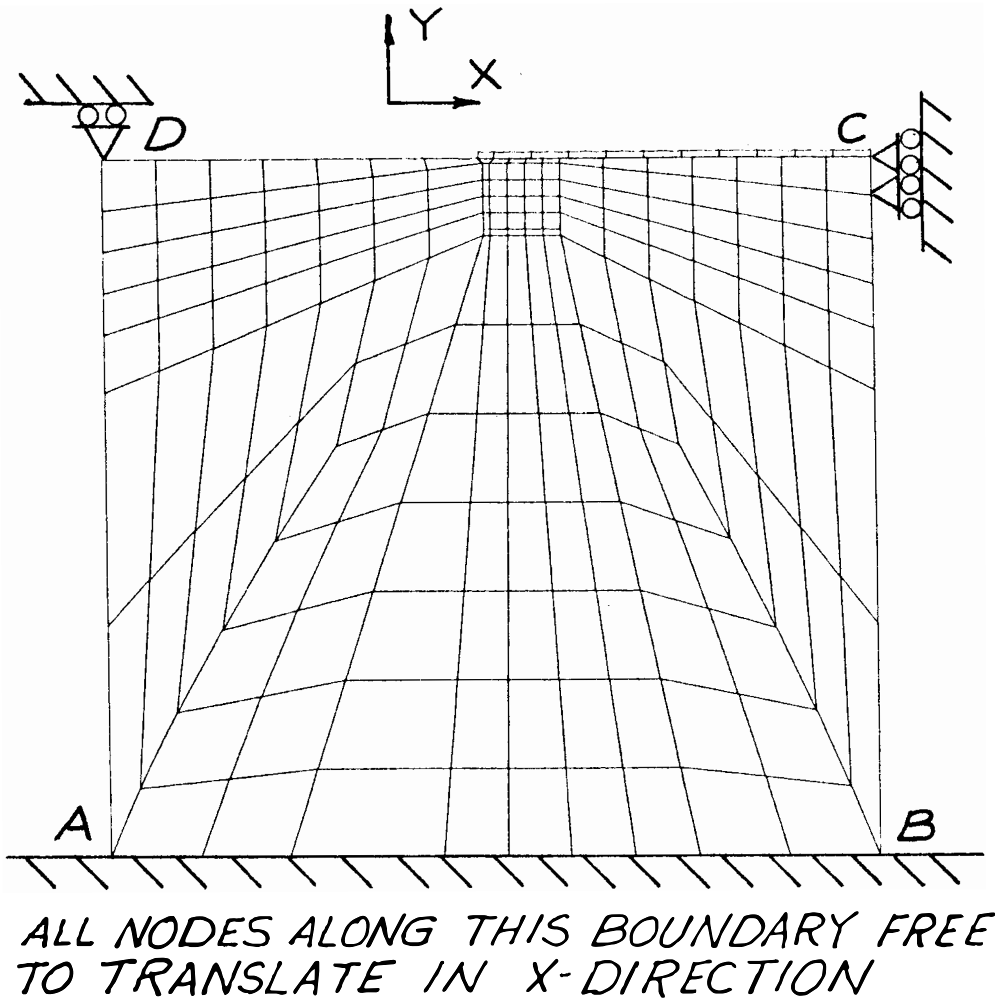

Figure 8. Finite Element Mesh Showing the External Boundary Conditions

specimen resting on the floor. The model is restrained at point C by two simple supports with freedom in the vertical direction. This represents the bearing plate that resisted the horizontal loads applied to the liner plate. Also a hold down simple support with freedom in the horizontal direction was placed at point D. This represented a hold down restraint applied to the test specimen for stability purposes.

Figure 9 shows the boundary conditions assumed between the angle and the concrete and between the liner plate and the concrete. A convenient and very useful feature of the PAFEC 75 computer program is the ability to "tie together" certain nodes in the finite element mesh and to specify that their translations and/or rotations are equal. This feature was very beneficial in describing the boundary conditions between the anchors, plate, and concrete. If these discontinuities are not modeled, the mesh is represented as a continuum between the steel and concrete; therefore, certain shear and tensile stresses will develop between the anchor, steel, and concrete which are not representative of the test specimen, and the resulting deflections will be much less than those obtained in the experimental data. In earlier finite element models analyzed by this researcher, this was shown to be true.

Using this "tie together" feature, or as it is referred to by PAFEC 75 as "REPEATED.FREEDOM," nodes 5 and 6 in Figure 9 were assumed to deflect equally in the x-direction only. In like manner nodes 2 and 4 deflect equally with nodes 1 and 3 respectively in the local Y_L-direction. In other words, nodes 2 and 4 and nodes 1 and 3 slide relative to each other along the line through nodes 1 and 3. These nodes translate and

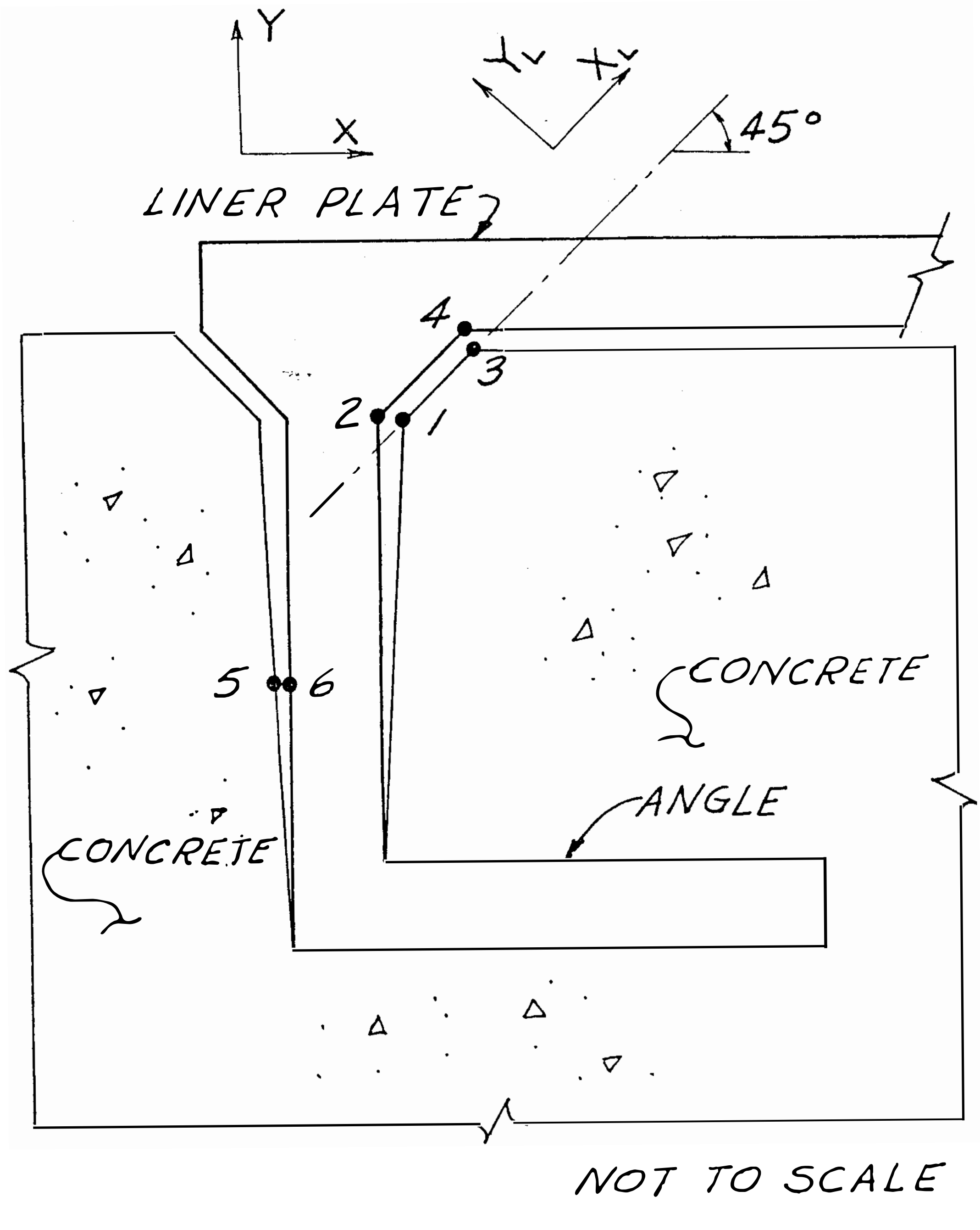

Figure 9. Boundary Condition between the Liner Plate, Embedded Angle and Concrete

rotate with respect to the flexibility of the total structure, but are tied together to represent the assumed behavior between the weldment and the concrete. Finally a selected number of nodes along the liner plate are tied together with selected nodes on the top surface of the concrete to restrain deflection in the Y-direction only. In other words, the liner plate must be free to deflect upward away from the concrete, but it is restrained by the concrete surface when the deflection is downward.

CHAPTER V

COMPARISON AND EVALUATION OF ANALYTICAL AND EXPERIMENTAL WORK IN BEHAVIOR OF LINER ANCHORAGES

Five separate analyses were made in order to compare with and evaluate the experimental work done at The University of Tennessee, Knoxville, in 1974 and 1980(2, 3). The first analysis is shown by the partial mesh in Figure 3 (p. 13). This represents the A2 series in the full scale model tests where the angle was welded continuously to the liner plate, and there were no voids between the concrete and steel. Figures 10 and 11 show the shape of the deflected structure under elastic conditions. Using the plasticity feature of PAFEC 75 and applying a 10 percent increment of load up to 10 kips per inch of liner, the bilinear analysis of concrete provides the results shown in Figure 12. The bilinear stress-strain curve assumed for the concrete is shown in Figure 13. Also, variations in concrete strength were investigated as shown in Figure 12. The analysis designated by DAR9 used a modulus of elasticity of 4.5×10^6 psi and a yield strength of 4000 psi whereas DAR8 reflects a modulus of elasticity of 5.76×10^6 psi and a yield strength of 6600 psi. The latter is data measured in The University of Tennessee tests, thus resulting in slightly smaller deflections of the embedded anchor.

The results of this inelastic solution are in close agreement with the actual test data. The test results record data all the way to ultimate failure of the anchorage and show increasing deflection under

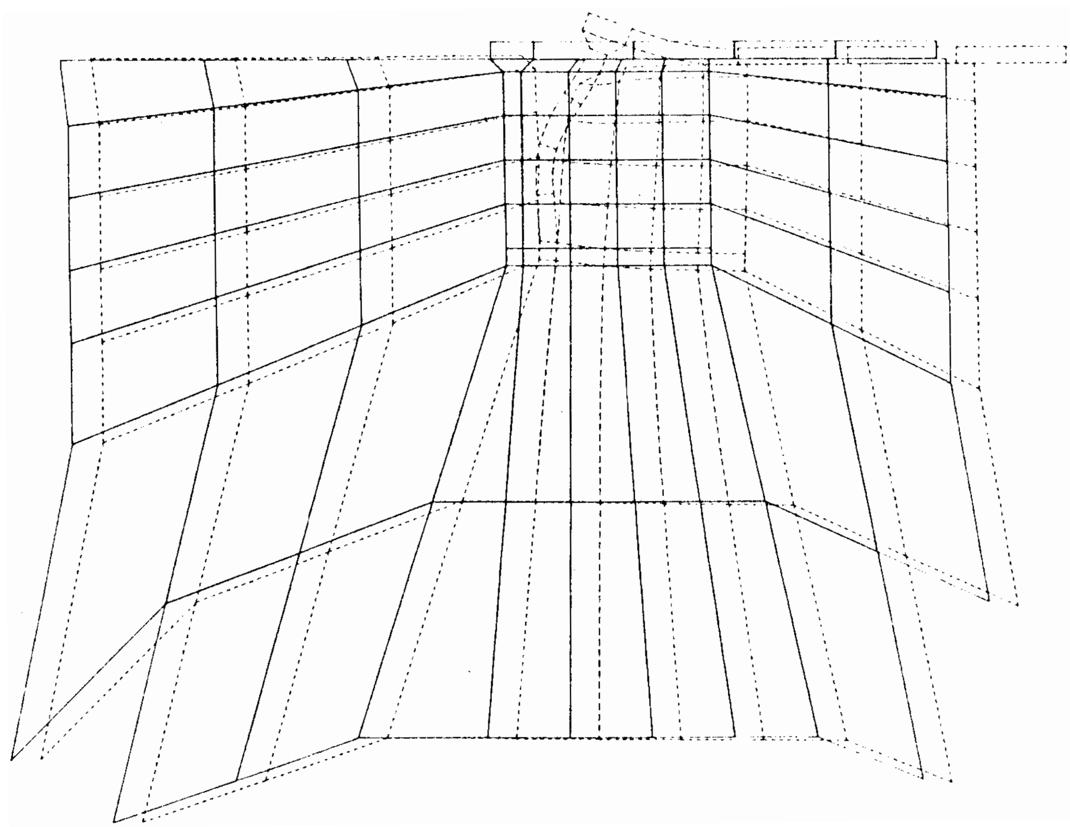

Figure 10. Shape of the Deflected Structure in the Region of the Anchor, Model DAR9

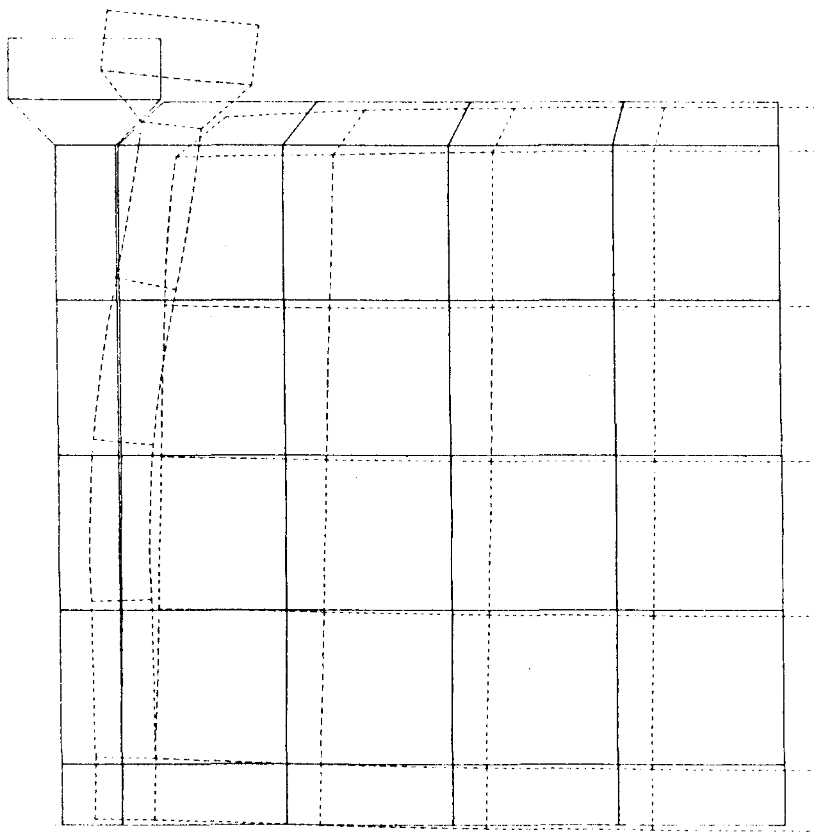

Figure 11. Shape of the Deflected Structure Excluding the Liner Plate, Model DAR9

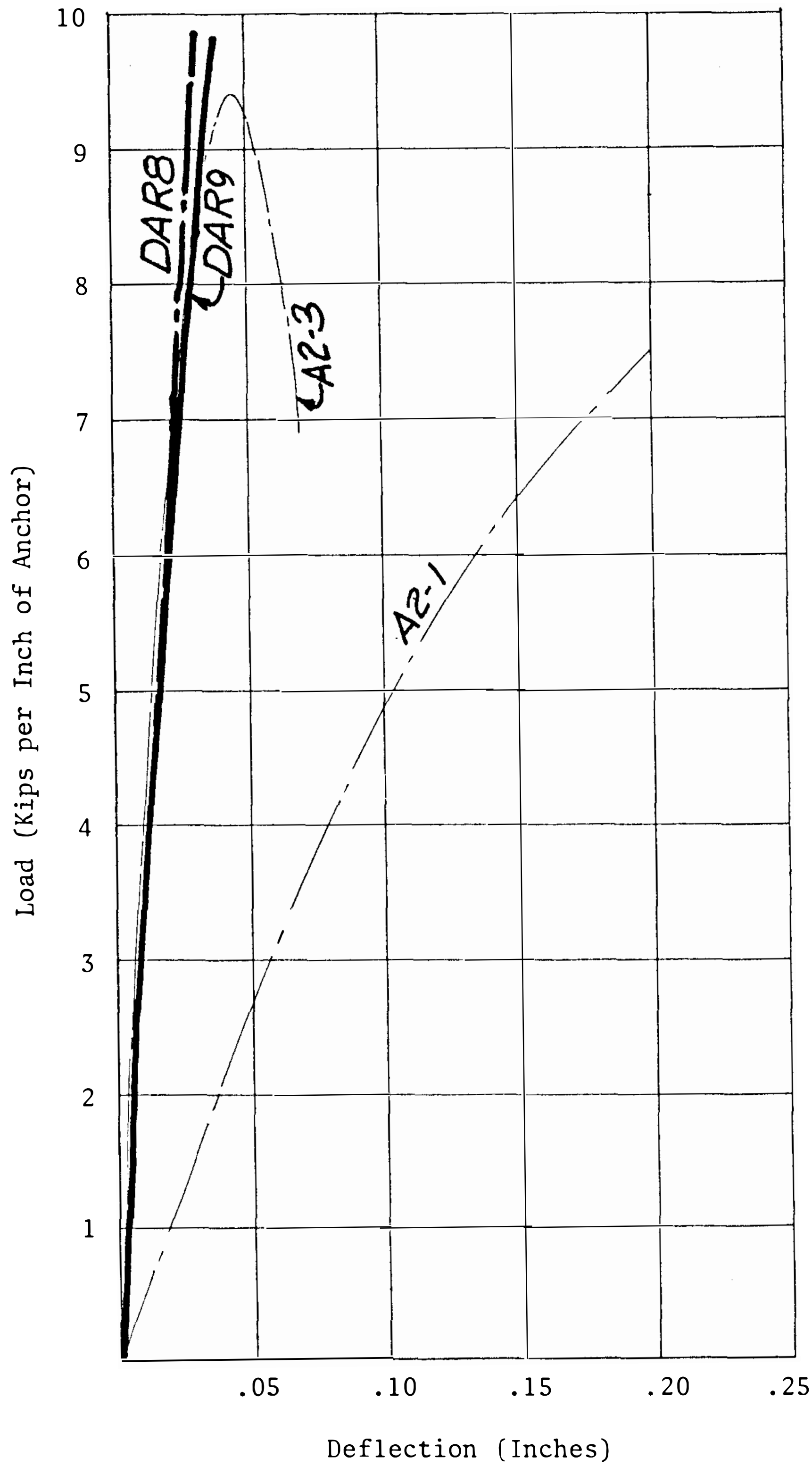

Figure 12. Analytical Results of Model DAR9 Compared to Test Results A2-1 and A2-3

Source: E. G. Burdette, "Liner Anchorage Testing," Second Interim Report, Division of Engineering Design, Tennessee Valley Authority, Knoxville, Tennessee, September 15, 1974

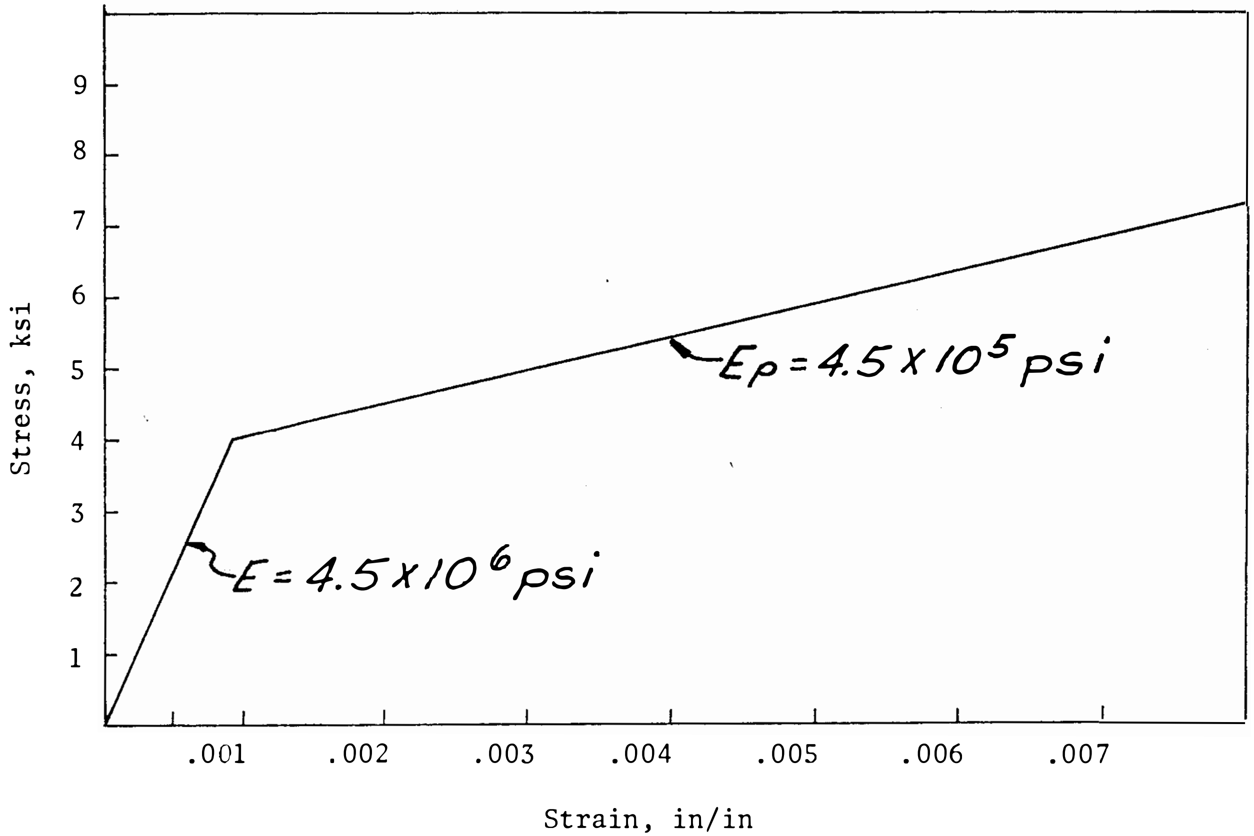

Figure 13. Bilinear Stress-Strain Relationship Used for Concrete

decreasing load. It is not possible to obtain this part of the curve with the current finite element program; thus, the results of this analysis will be limited to the increasing loads and their associated deflections.

A second analysis is shown by the partial mesh in Figure 4 (p. 14). This represents the A1 series and the A3-1 and A3-3 tests in the full scale model tests where the angle is not welded continuously to the liner plate. A worse case assumed was the mesh showing a filet weld on only one side of the angle as represented in Figure 4.

Figures 14 and 15 show the shape of the deflected structure under elastic conditions. The bilinear solution is shown in Figures 16 and 17 along with the actual test data for the A1 and A3 series respectively. The PAFEC 75 plastic solution tends to be generally good along the load-deflection curve established by actual test results; however, the deflections do not "peak out" as measured in the actual tests. The analytical deflections do not increase as rapidly under the maximum load. Some of this difference between analytical and actual test data at these larger deflections is due to the lack of convergence in the PAFEC 75 solution. Another source of this difference is due to the inability of the analytical solution to approximate the conditions that exist when the strain in the concrete reaches a level where crushing occurs. This is primarily the cause of the deflected structure where the analytical case is stiffer under the higher loads than the experimental case.

One approach that this investigator used to approximate the "peak" of the load-deflection curve was to make successive analyses where a

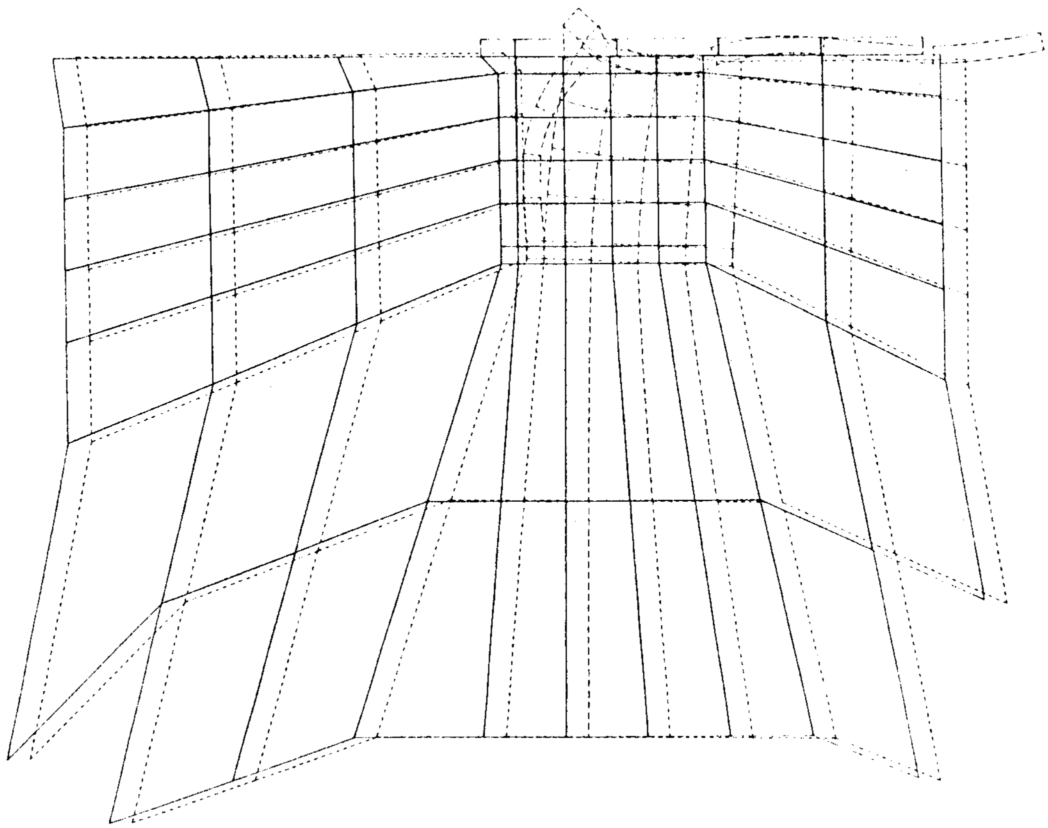

Figure 14. Shape of the Deflected Structure in the Region of the Anchor, Model RAD9

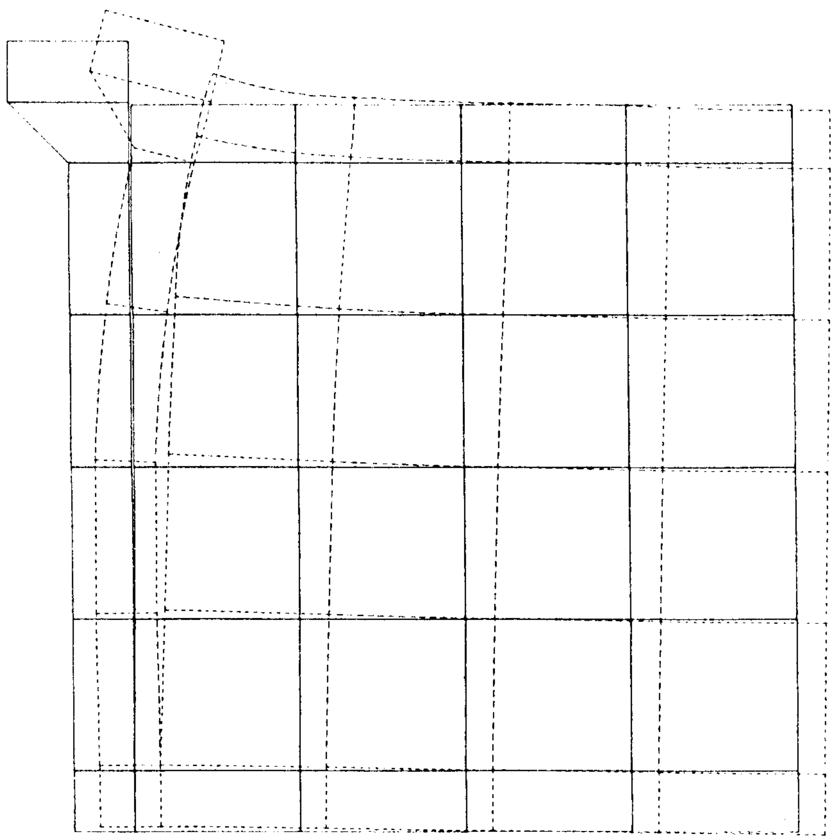

Figure 15. Shape of the Deflected Structure Excluding the Liner Plate, Model RAD9

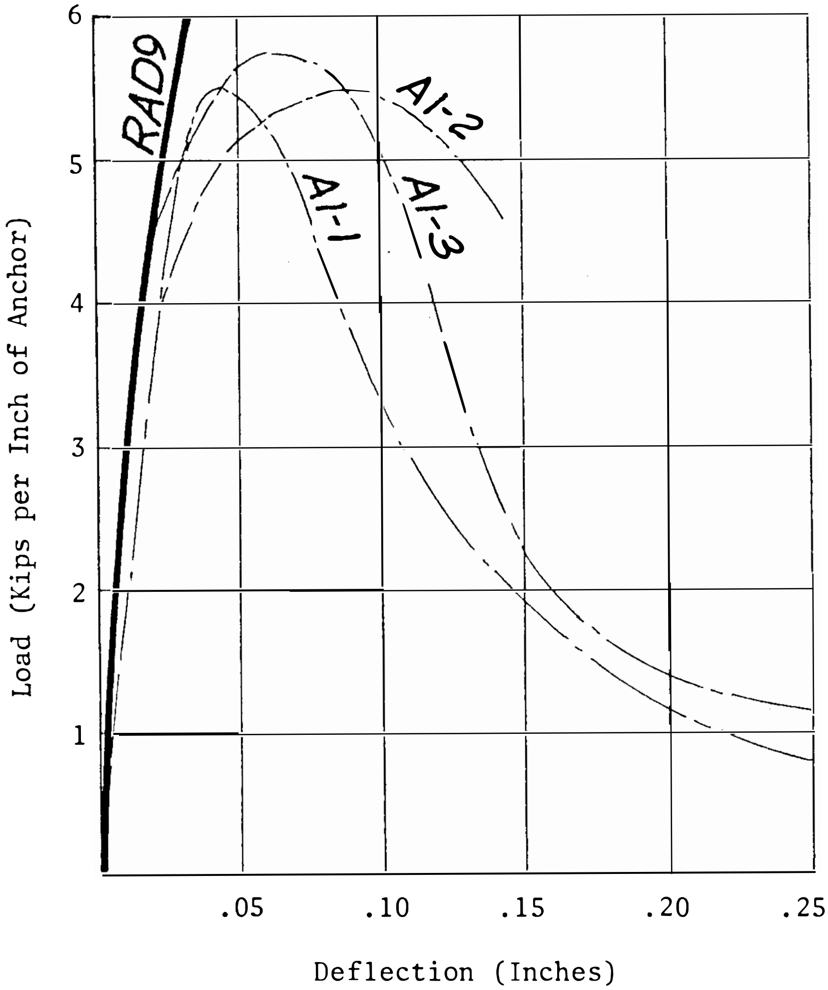

Figure 16. Analytical Results of Model RAD9 Compared to Test Results A1-1, A1-2, and A1-3

Source: E. G. Burdette, "Liner Anchorage Testing," Second Interim Report, Division of Engineering Design, Tennessee Valley Authority, Knoxville, Tennessee, September 15, 1974

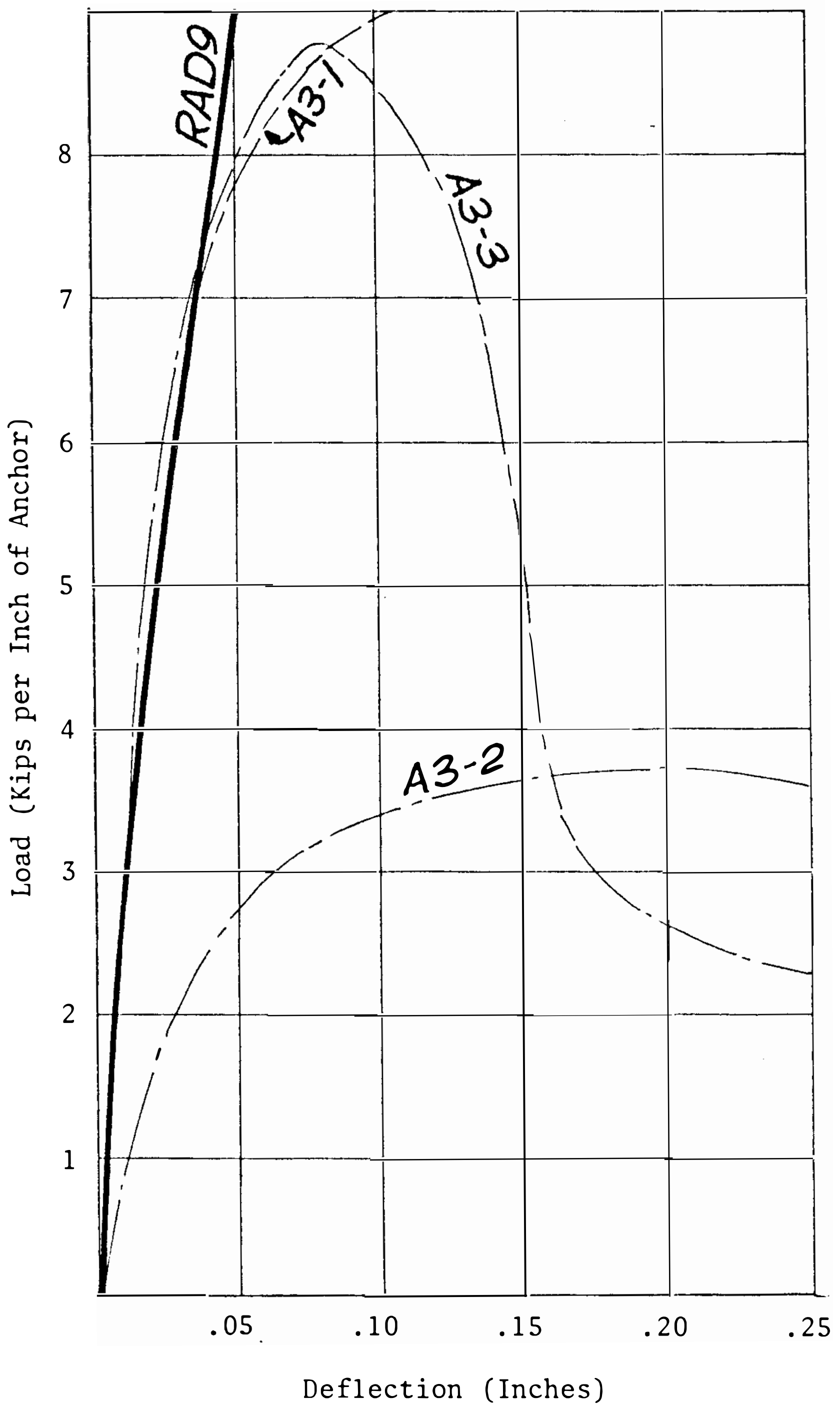

Figure 17. Analytical Results of Model RAD9 Compared to Test Results A3-1, A3-2, and A3-3

Source: E. G. Burdette, "Liner Anchorage Testing," Second Interim Report, Division of Engineering Design, Tennessee Valley Authority, Knoxville, Tennessee, September 15, 1974

selected part of the concrete is eliminated. Figure 18 shows the approach taken by drawing an "umbrella curve" that departs from the RAD9 curve at a load of 4 kips per inch where the maximum strain reached .0102 in/in in element 122, Figure 19, and is drawn to the ARD7 curve at 5 kips per inch where the maximum strain reached .0104 in/in in element 114, Figure 20. Also, a third analysis, RAD7, was made eliminating elements 118, 122, and 123 in Figure 19. The three successive analyses are summarized in Table 1. Although this approach gives a very rough approximation, even a lower bound of the load-deflection behavior, it does provide a conservative method for describing the curve under "peaking" loads.

A third and fourth analysis investigated the effect of a 1/2-inch gap as shown in Figures 5 and 6 (pps. 15 and 16). Figure 6 does not show a gap, but the anchor was "tied" to the concrete 1/2-inch below the top surface of the concrete block. This analysis gave a better approximation to the A6 series of tests where the gap length varied from 0 to 6 inches. The mesh in Figure 5 represents a continuous gap as shown in the A3-2 test. The shape of the deflected structures is shown in Figures 21-24. The load deflection behavior is compared with the A6 series in Figure 25. The variation in the experimental test results was rather wide, and the analytical results agreed reasonably well in the region of the investigation. Again, if an "umbrella curve" based on the results of ARD9, ARD7, and RAD7 is drawn, a rough approximation can be made of the "peak load" occurring in the tests series A6. The analysis and results are shown in Figure 26 and Table 2. Partial

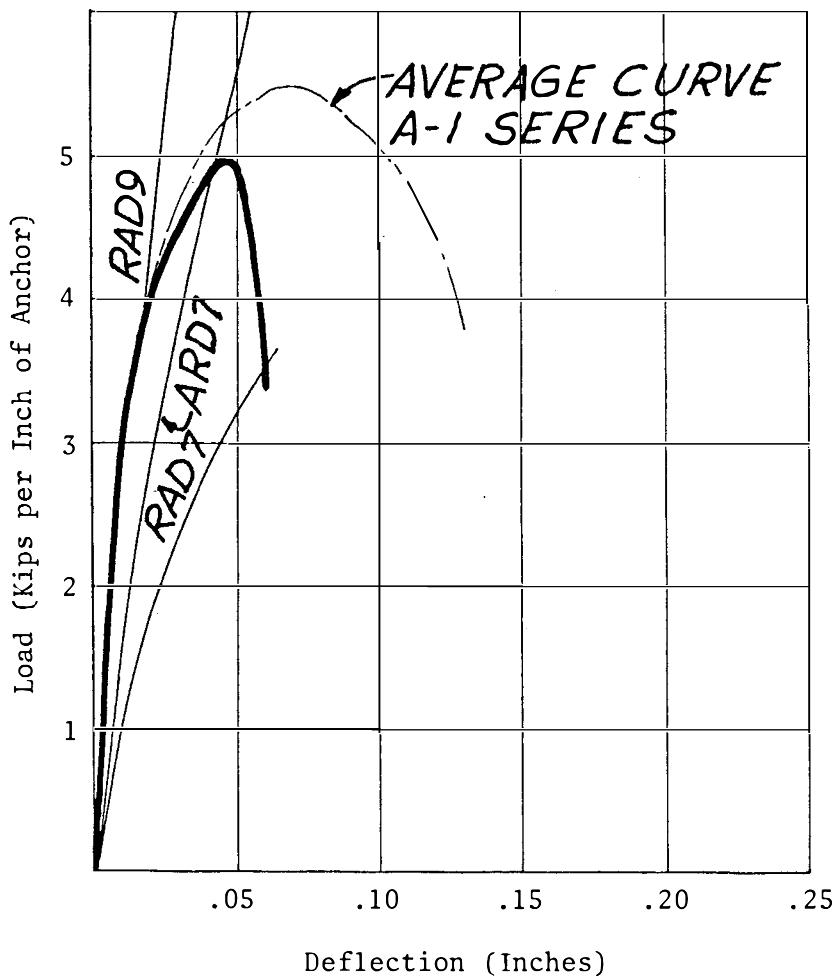

Figure 18. Umbrella Curve of Results of RAD9, ARD7, and RAD7 Compared to the Average Curve A1 Series

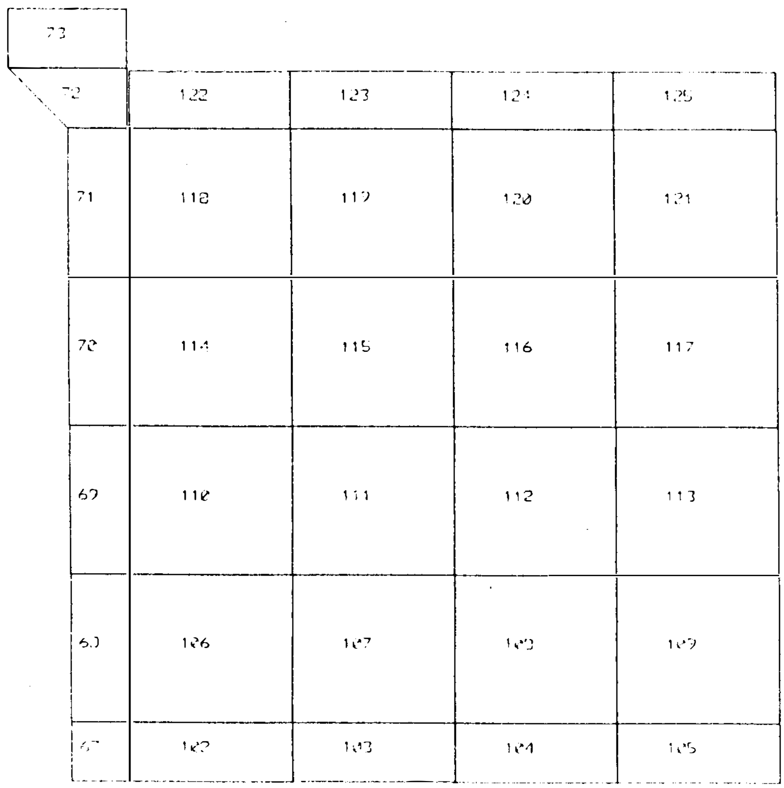

Figure 19. Partial Finite Element Mesh Excluding Liner Plate, Model RAD9

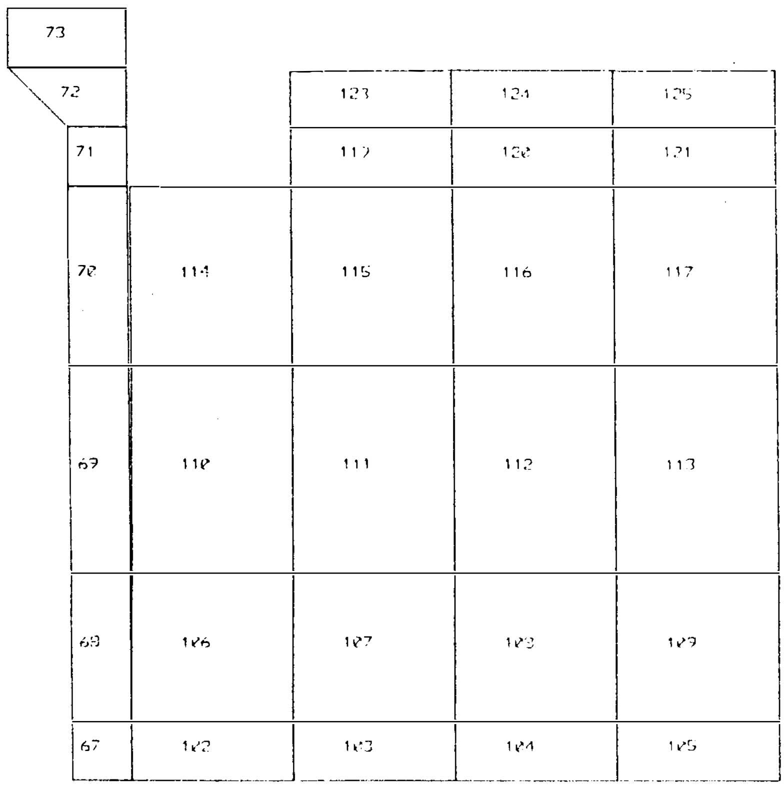

Figure 20. Partial Finite Element Mesh Excluding Liner Plate, Model ARD7

Table 1

Maximum Load and Strain Levels Where Concrete Assumed to be Crushed in Successive Analyses, Results of RAD9, ARD9, and RAD7

Model Analyzed	Element	Load Kips/in	Equivalent Plastic Strain in/in
RAD9	122	4.0	.0102
ARD9	114	5.0	.0104
RAD7	114	3.5	.0100

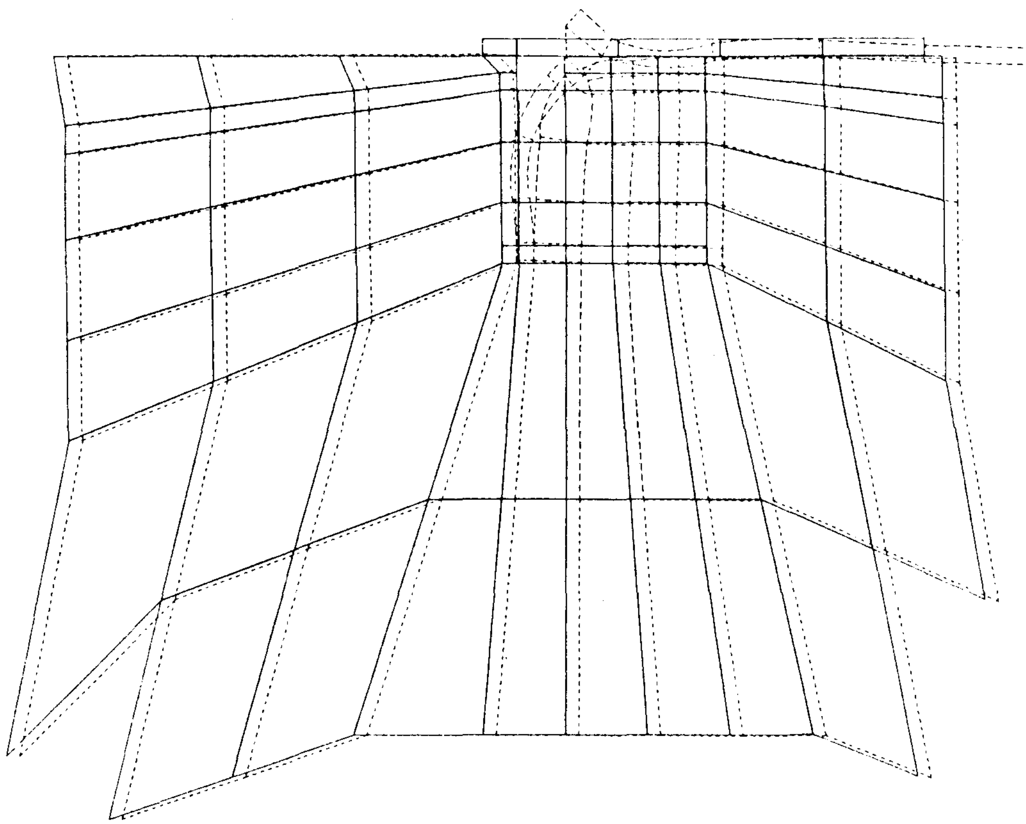

Figure 21. Shape of the Deflected Structure in the Region of the Anchor, Model ARD7

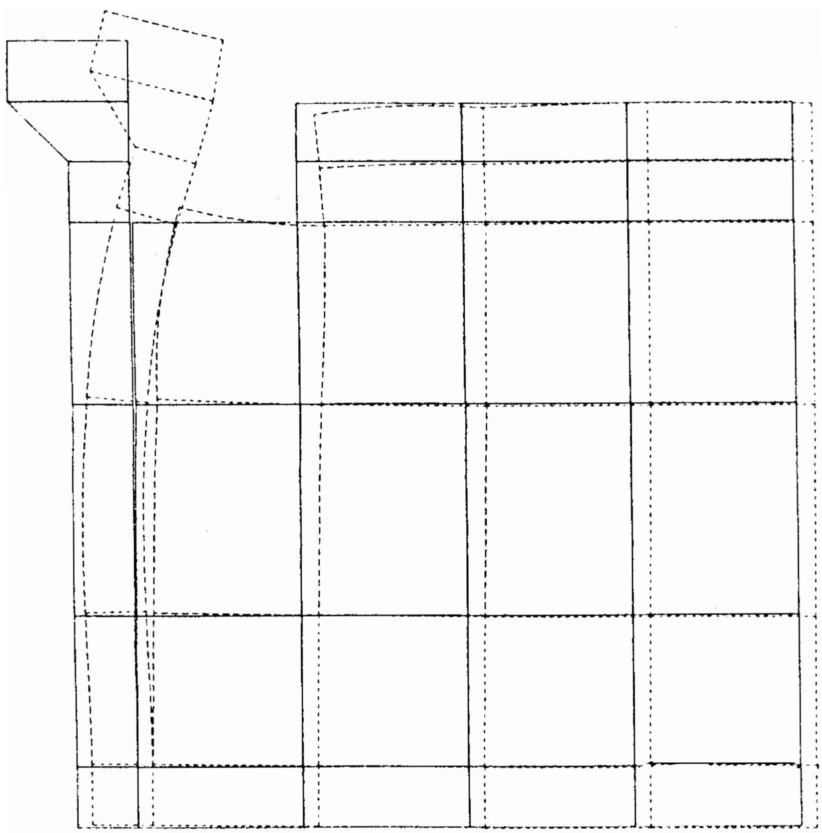

Figure 22. Shape of the Deflected Structure Excluding the Liner Plate, Model ARD7

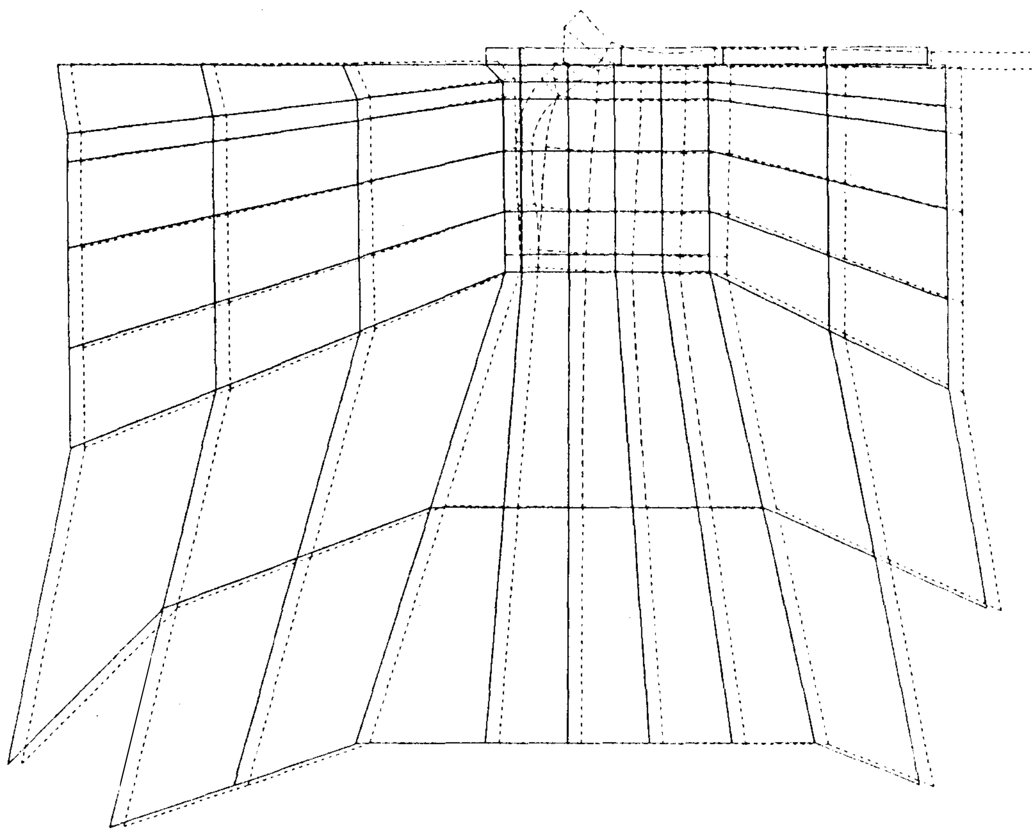

Figure 23. Shape of the Deflected Structure in the Region of the Anchor, Model ARD9

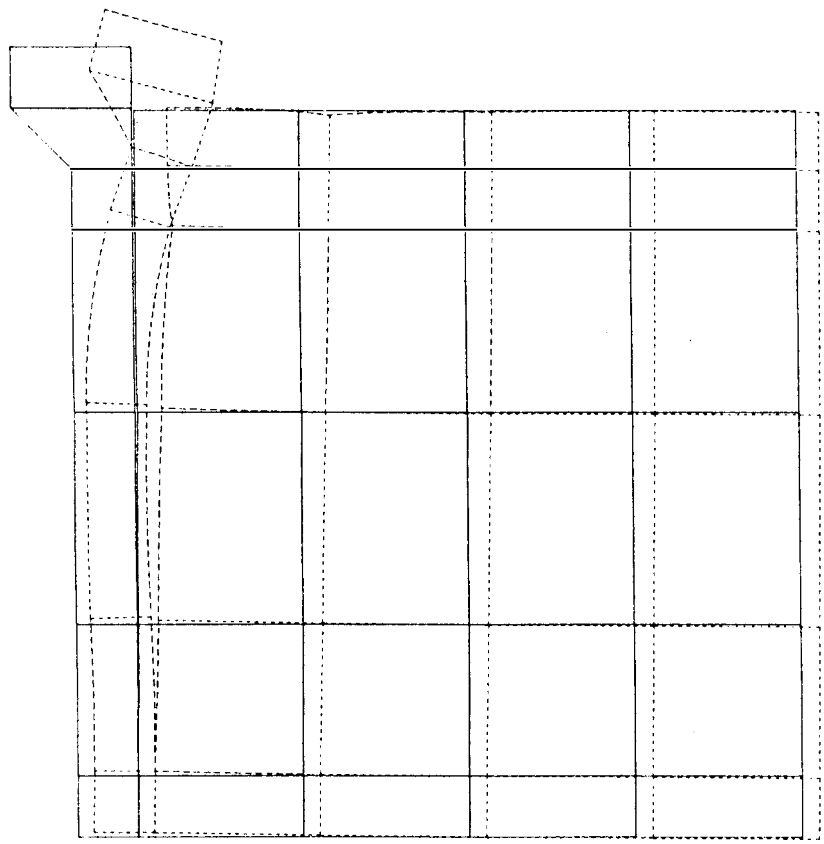

Figure 24. Shape of the Deflected Structure Excluding the Liner Plate, Model ARD9

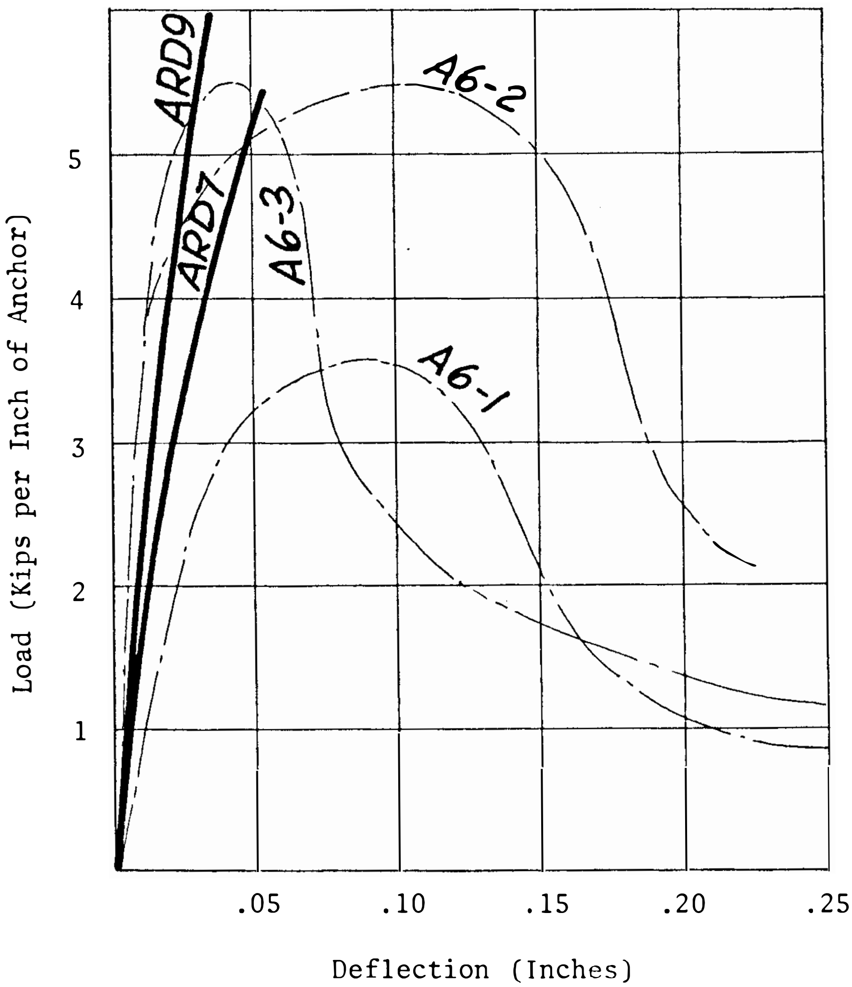

Figure 25. Analytical Results of Model ARD9 Compared to Test Results A6-1, A6-2, and A6-3

Source: E. G. Burdette, "Liner Anchorage Testing," Second Interim Report, Division of Engineering Design, Tennessee Valley Authority, Knoxville, Tennessee, September 15, 1974

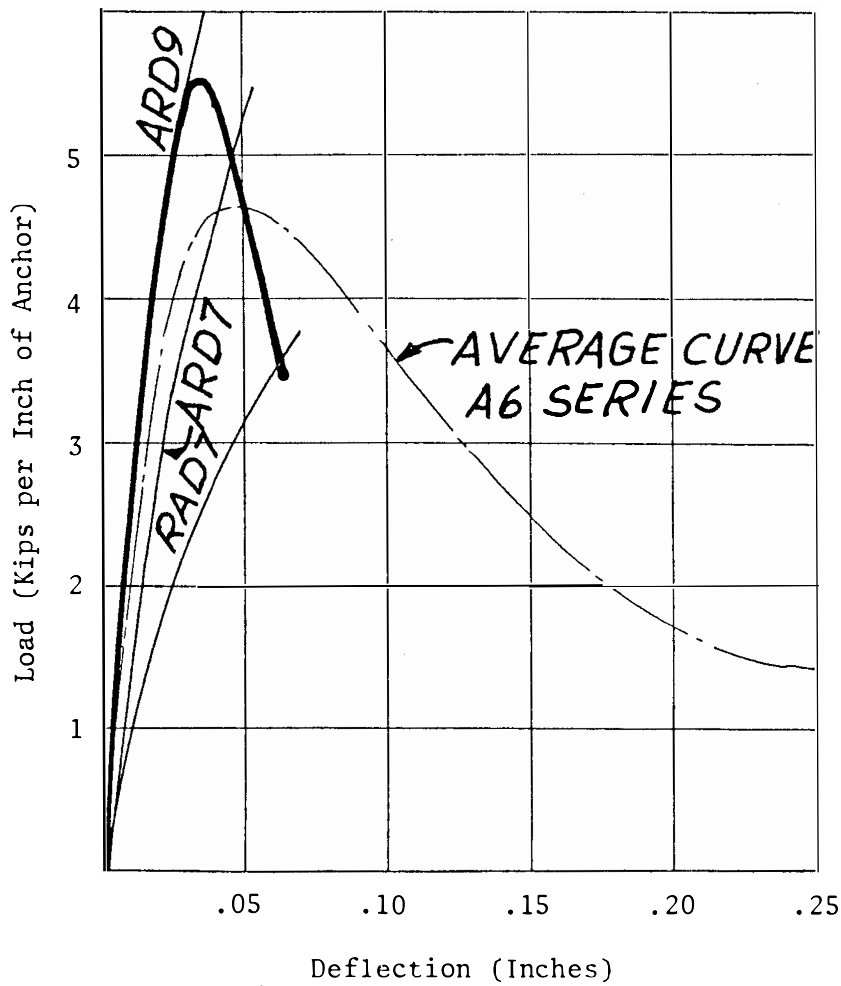

Figure 26. Umbrella Curve of Results of ARD9, ARD7, and RAD7 Compared to the Average Curve A6 Series

Table 2

Maximum Load and Strain Levels Where Concrete Assumed to be Crushed in Successive Analysis, Results of ARD9, ARD7, and RAD7

Model Analyzed	Element	Load Kips/in	Equivalent Plastic Strain in/in
ARD9	118	5.5	.0100
ARD7	114	5.0	.0104
RAD7	114	3.5	.0100

finite element meshes for ARD9 and ARD7 are shown in Figures 27 and 20 (p. 35), respectively. As in the previous case, RAD7 was used to give a third point on the curve since it would represent both cases with certain concrete elements eliminated. The analytical "peak load" is greater than the "peak load" represented by the average curve; however, two of the individual tests did show maximum loads of 5.5 kips per anchor length, the same result shown by the umbrella analysis. In fact, the A6-3 test had a load-deflection curve very close to the analytical umbrella curve.

Finally, a fifth analysis considered the behavior of a structural tee anchor instead of the angle investigated in the previous cases. This analysis is compared to the experimental load-deflection tests conducted by The University of Tennessee for United Engineers and Constructors (2). A WT4 × 7.5 tee anchor continuously welded to a 3/8-inch liner plate was investigated using again a plane stress finite element analysis. One advantage that was realized in using the PAFEC 75 program was that the original mesh describing the angle anchorage system was modified to describe the tee anchorage by changing only a few data elements. This greatly facilitated the data preparation and has the potential for tremendous cost savings in labor when using this program in an engineering practice. Figure 7 (p. 17) shows the partial mesh that described the region of the tee anchorage. Figures 28 and 29 show the shape of the deformed structure and Figure 30 compares the load-deflection relationships of the analytical with the experimental results.

The analytical results of the tee anchor shown in Figure 30 were in close agreement with the test data by Burdette (2). Also, this analysis

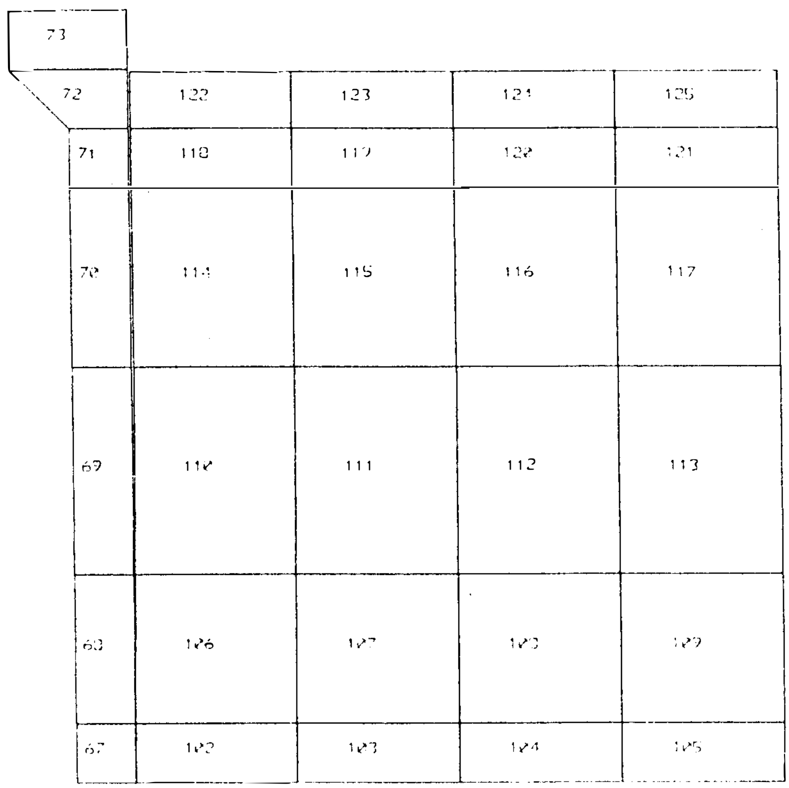

Figure 27. Partial Finite Element Mesh Excluding Liner Plate, Model ARD9

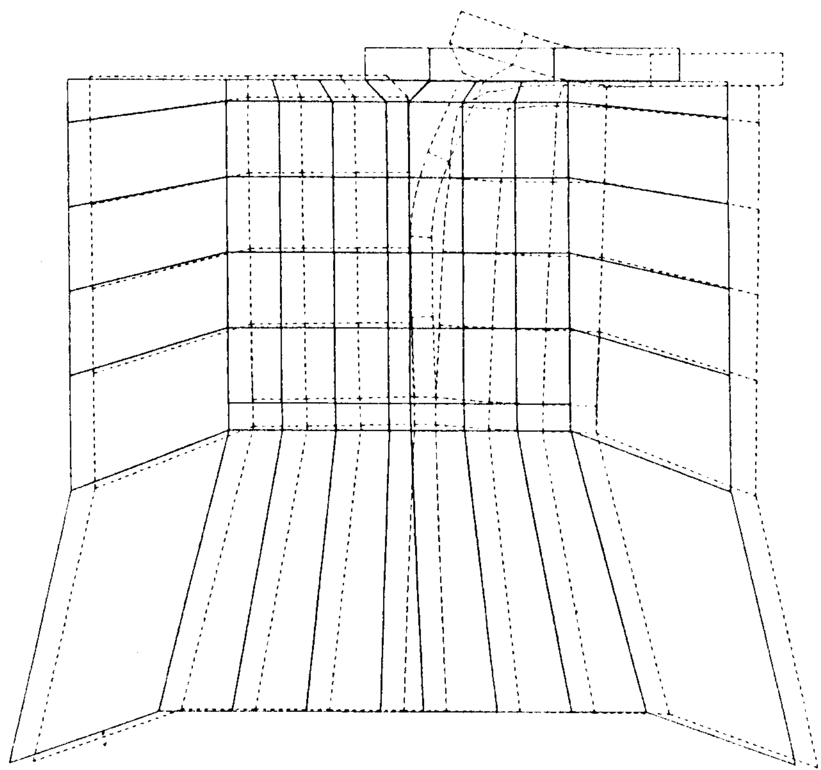

Figure 28. Shape of the Deflected Structure in the Region of the Anchor, Model ARD8

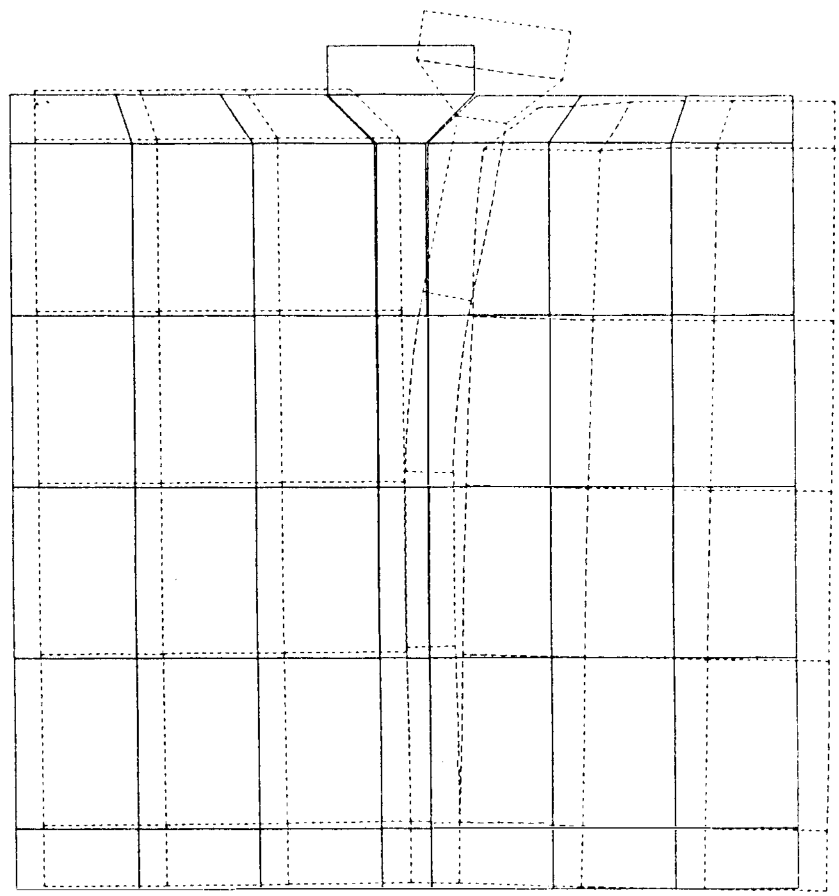

Figure 29. Shape of the Deflected Structure Excluding the Liner Plate, Model ARD8

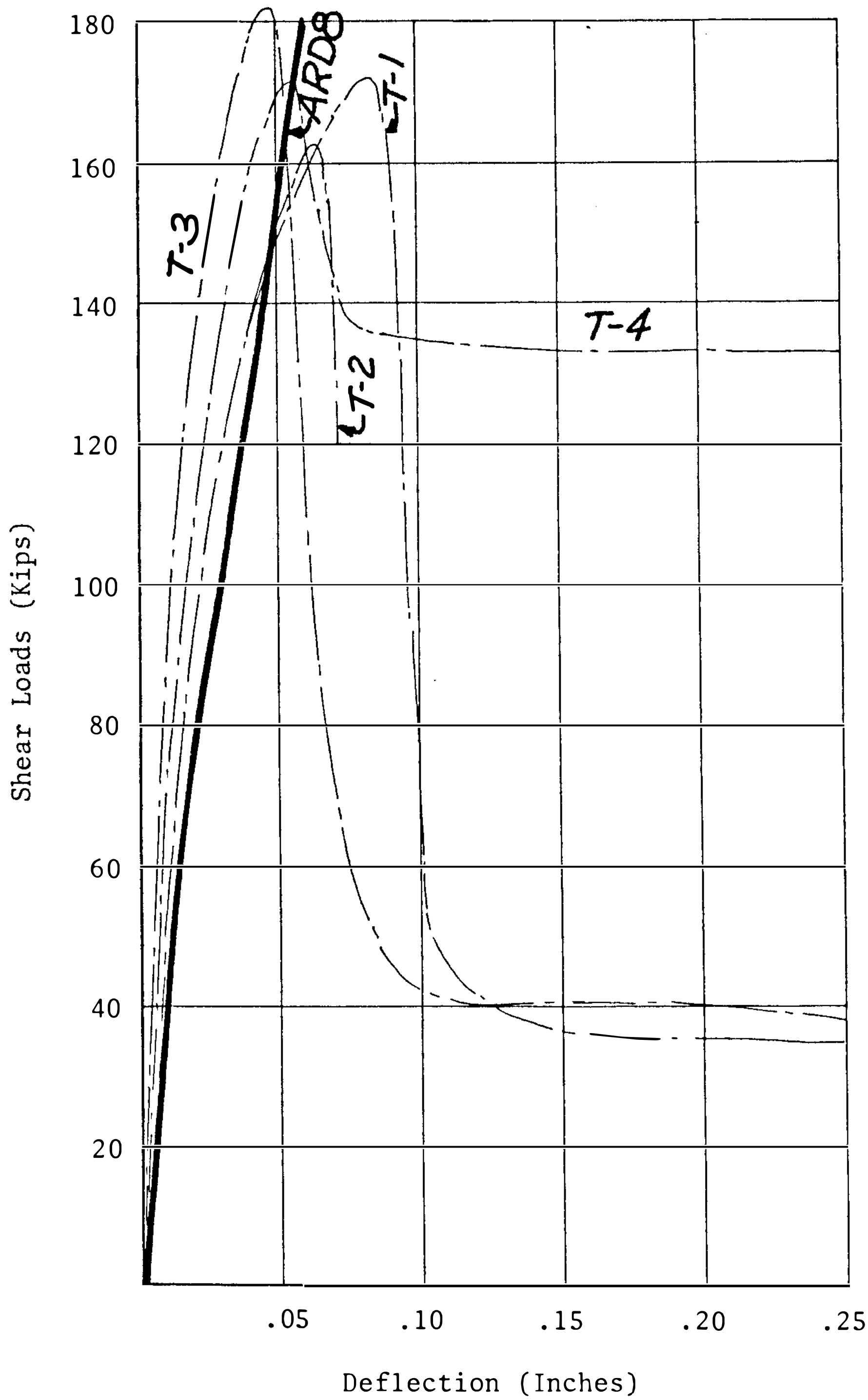

Figure 30. Analytical Results of Model ARD8 Compared to Test Results T-1, T-2, T-3, and T-4

Source: E. G. Burdette, "Containment Liner Anchor Load Tests," Final Report, Tests Performed for United Engineers and Constructors, Department of Civil Engineering, The University of Tennessee, Knoxville, Tennessee, 1981.

correlates well with the angle anchor analysis (DAR9), Figure 12 (p. 25), where the boundary conditions between the anchor and the concrete were similar. Under the same loads, the resulting deflection for both the tee and angle anchor were approximately equal, which is also substantiated by the test data.

CHAPTER VI

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

In summary, it appears that one can approximate the load-deflection behavior of a particular anchorage system using a finite element, plane stress analysis with a bilinear stress-strain relationship for concrete. The analytical results compare very closely with the experimental data up to the point where the test results approach the maximum or "peak" load of the curve. In this region of the curve the rate of deflection increases rapidly with corresponding increases in load. The major cause of this behavior is believed to be local crushing of the concrete caused by the flexure of the anchor. Since the finite element analysis is limited to a bilinear stress-strain relationship, it is not possible to factor in the effect of the concrete crushing in a single analysis. The approximation method described in Chapter V enables the investigator to include the influence of the crushed element by eliminating them in successive analyses.

Two major contributions have been made by this work. First, it was shown that the experimental work conducted at The University of Tennessee, Knoxville, can be approximated by analytical methods, at least in the elastic-plastic region up to the maximum load. Beyond the work of this investigation, additional research should be done in order to incorporate the effects of the crushing behavior of concrete, particularly in declining portion of the load-deflection curve. Second, the techniques used in describing the finite element mesh have practical applications for use by investigators who wish to study anchorage types and sizes other than those used in this work. The PAFEC 75 finite element program provides a relatively simple data preparation method which can be changed very easily in order to investigate different conditions and types of anchorage systems. Also, the boundary conditions described in Chapter IV between the embedded anchor steel plate and concrete are extremely important to consider in making a finite element analysis of an anchorage system. Earlier attempts by this investigator did not properly address these boundary conditions with the results giving much stiffer load-deflection behavior than the experimental data.

Finally, if one wished to extend this investigation into an analysis of a portion of the containment structure with liner and anchors, this work provides one block of the total structure that can be repeated in series to give the desired number of anchors considered in an analysis. This method was also suggested by Tan (19), but no details were given. The advantage of considering this larger mesh would be the ability to investigate the actual interaction between anchors and the steel liner under thermal expansion and other applied forces induced by the liner system in the concrete. This analysis should be done selectively since the computer costs would be quite large.

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